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LAWRENCE LIVERMORE NATIONAL LABORATORY

New Concepts for Reducing Costs and Increasing Efficiency of Solid-State Laser Drivers for IFE

A.C. Erlandson, E. Ault, C. Barty, A. Bayramian, R. Beach, J. Caird, R. Campbell, R. Cross, T. Ladran, Z. Liao, J. R. Murray, R. Page, K. Schaffers, T. Soules, S. Sutton, S. Telford

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Innovative Confinement Concepts (ICC) Workshop
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Disclaimer

New Concepts for Reducing Costs and Increasing Efficiency of Solid-State Laser Drivers for IFE

February 14, 2007

Innovative Confinement Concepts Workshop

University of Maryland

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Photon Science and Applications Program

National Ignition Facility Programs Directorate

Lawrence Livermore National Laboratory

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Laser "skunkworks" activities have been undertaken to develop low cost, high-efficiency laser drivers

Our work builds upon experience building large flashlamp-pumped laser systems and smaller diode-pumped systems

- NIF, Mercury and SSHCL

We have concentrated first on opening up the design space

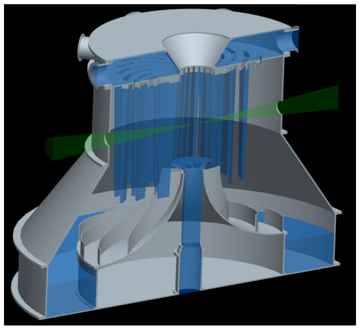
- blue-sky ideas, application of developing technologies

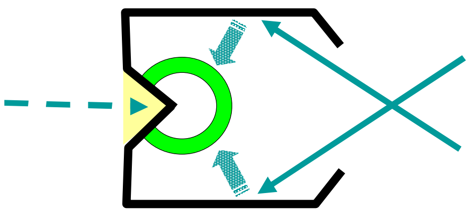
Significant reductions in costs and increases in efficiency appear feasible

- only tens of beamlines, > 20% efficiency

We plan to undertake more detailed performance calculations and design development in coming months

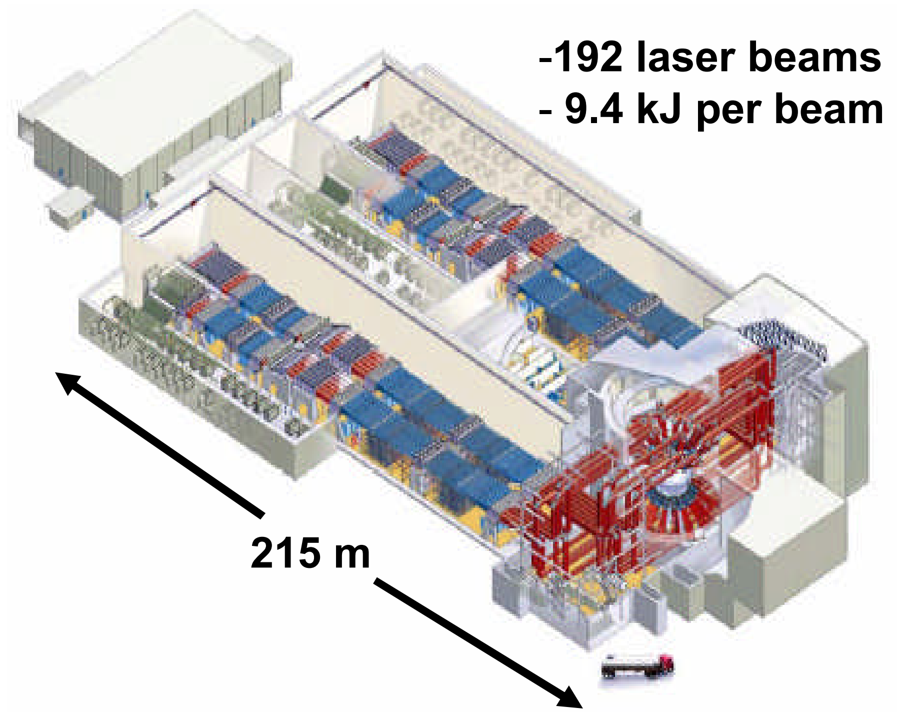
IFE laser driver requirements flow down from power-plant requirements and design choices





Design Choices	Requirements
IFE Power Plant	Power generating capacity: 1 GW Fusion power: 2 GW First wall: Long lifetime, maintainable $\eta G > 10$ to limit recirculating power
Liquid-Wall Target Chamber	Repetition Rate: 5 Hz Target Yield: 400 MJ 2-sided illumination
Indirect Drive	Affordable laser driver, so target gain G = 200
Fast Ignition Target	Compression and Ignition Laser Pulses
Compression Laser	2 MJ / 20 ns compression pulse Wall-plug efficiency $\eta > 5\%$ Optics lifetime of $10^9 – 10^{10}$ shots so ~0.5 μm wavelength
Ignition Laser	300 kJ / 10 ps ignition pulse 0.5 – 1 μm wavelength

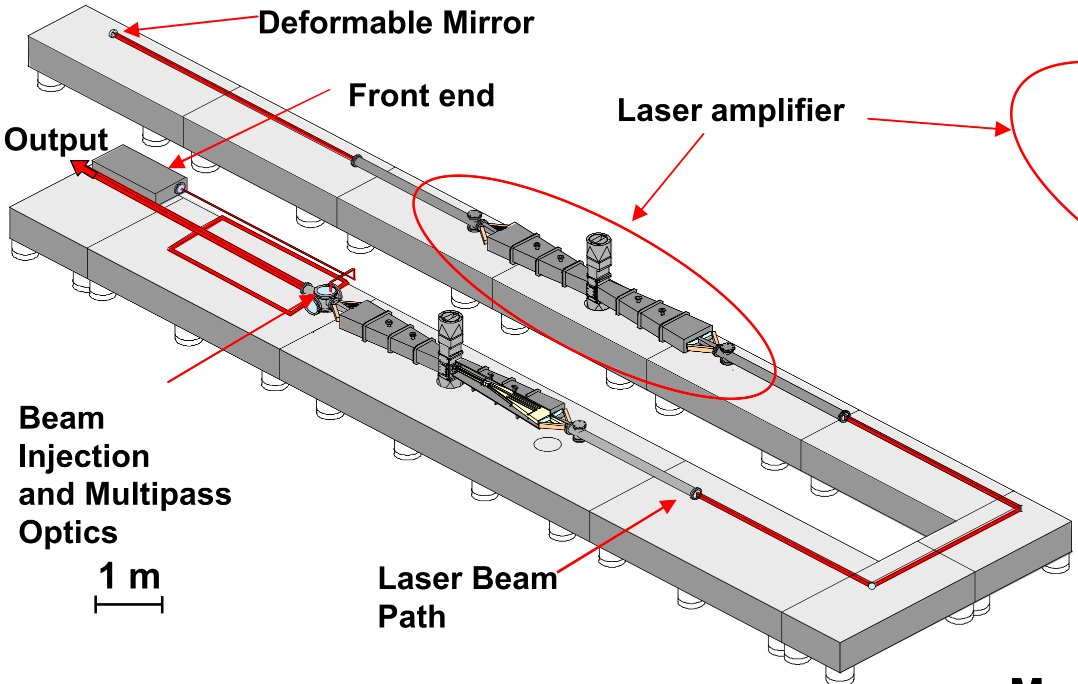
NIF's driver laser produces 1.8 MJ and is comparable to the IFE compression laser in size and energy

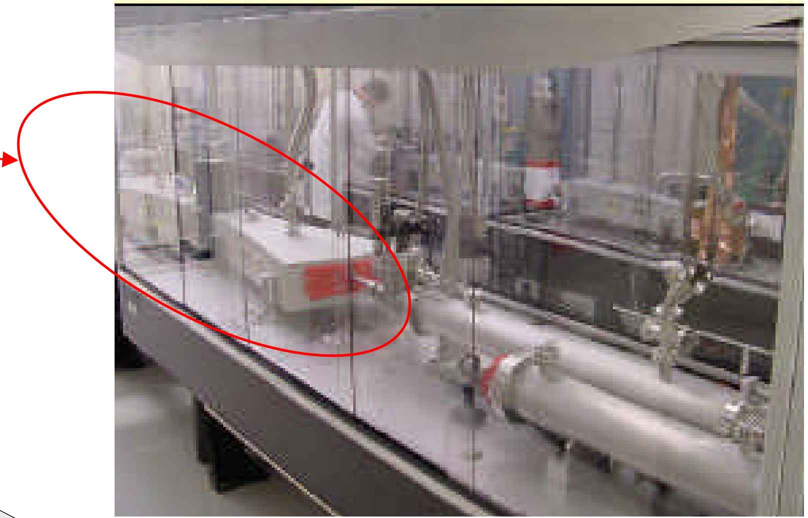


	NIF	IFE Compression Laser
Energy	1.8 MJ	2 MJ
Wavelength	0.35 μm	0.5 μm
Wall-plug efficiency	0.75%	> 5%
Repetition rate	1 shot / 2 hours	5 Hz
Cost	~ $500 / J	< $500 /J

- NIF uses passively-cooled, flashlamp-pumped laser slabs
- The IFE compression laser uses diode-pumped, actively-cooled slabs to meet efficiency and repetition rate requirements
- Nonetheless, NIF provides much useful information to designers
  - costs, learning curves, and "lessons learned"
  - importance of using optics that have good manufacturing characteristics
  - analysis tools, work-breakdown structure, requirements documents

Mercury is a test-bed for developing high-average-power diode-pumped solid-state laser technology for IFE

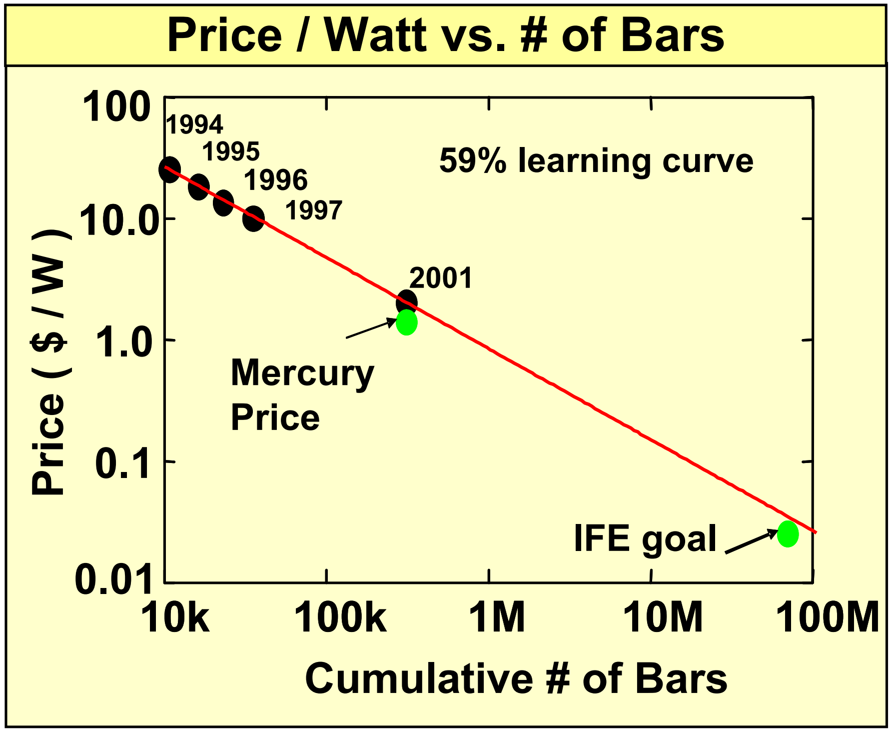


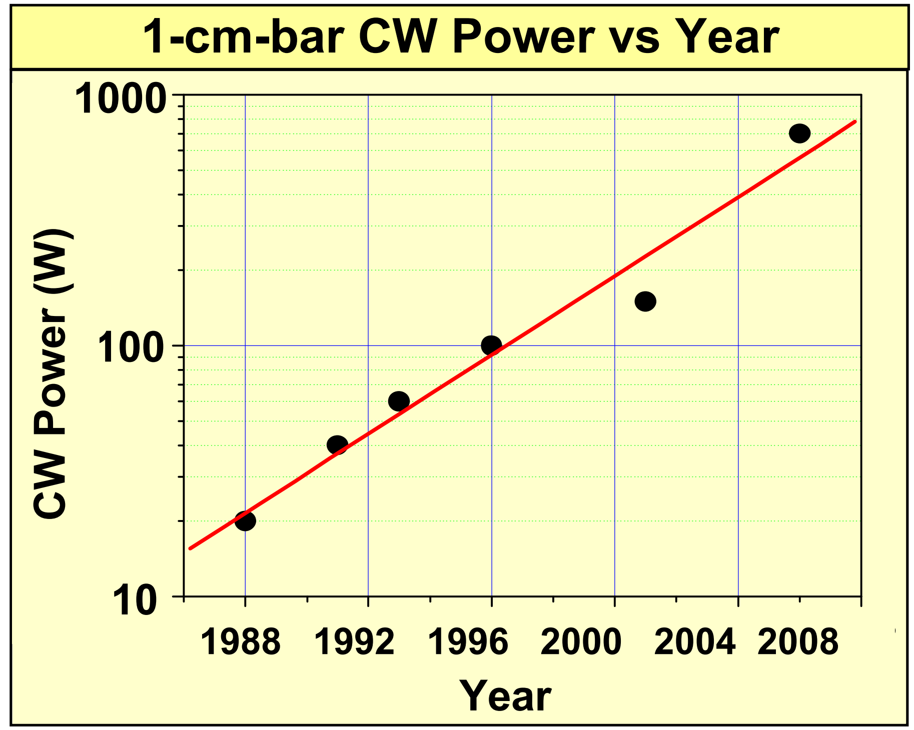


	Goals	Status
Energy (J) (@ 1 ω)	100	65
Opt. Efficiency (%)	10	6.5
PRF (Hz)	10	10 Hz
Pulse length (ns)	3-10	14
Wavelength (μm)	0.52/0.35	0.52
Bandwidth GHz	>150	In Process
Beam quality (xDL)	5	4

- Mercury addresses issues important to IFE drivers:
  - high-power laser diodes
  - thermal management for optics
  - optics lifetime
  - growth of Yb:S-FAP, a high-gain slab material

Diodes are becoming cheaper, more powerful, and more efficient





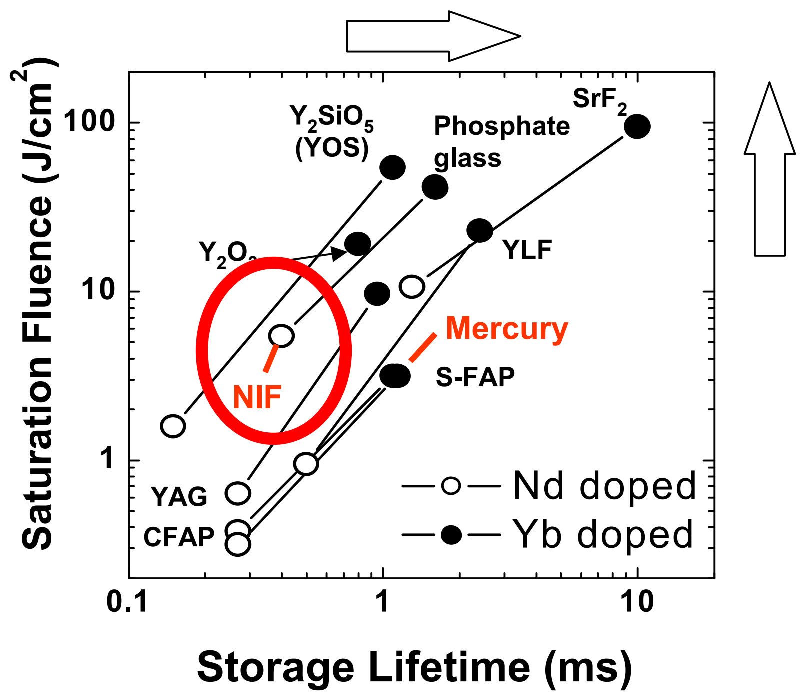
- Several companies supported by the DARPA Super-High-Efficiency Diode Sources (SHEDS) Program have developed diodes with electrical-to-optical efficiency > 70%

- Goal of quantum-dot diode program at the University of Central Florida is > 90% efficiency

High saturation-fluence, long-storage-lifetime materials have both advantages and disadvantages

Lower diode cost and/or higher storage efficiency – good !

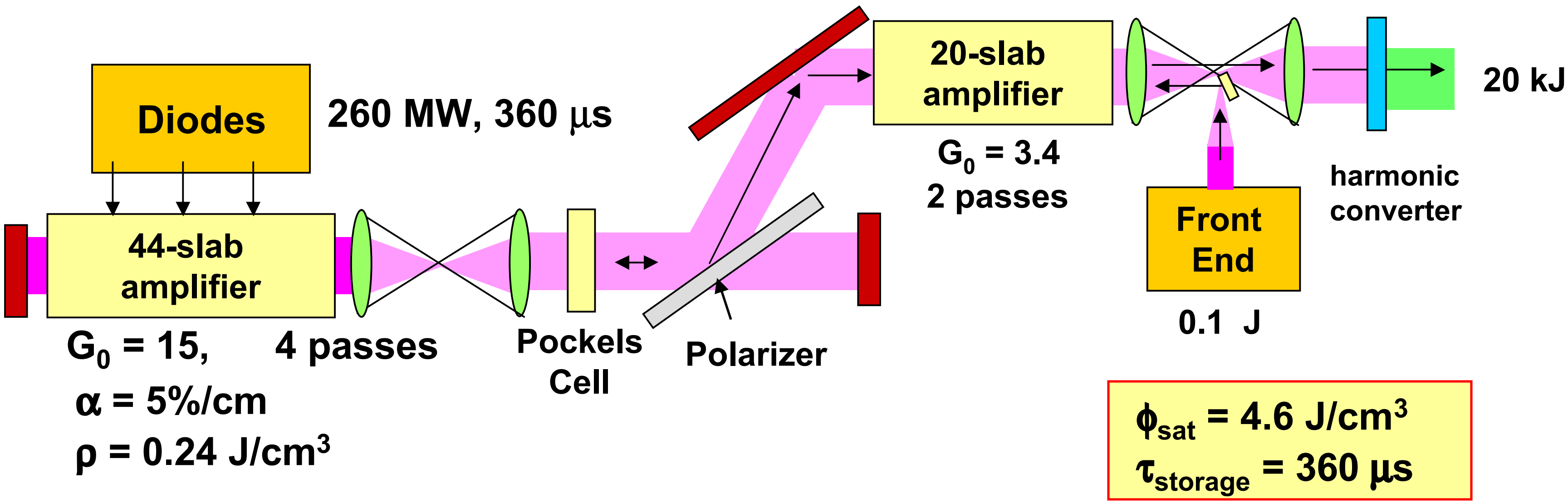
$\phi_{sat} \propto \tau_{storage}$



Higher stored energy density, fewer laser slabs needed, higher storage efficiency – good !

Lower extraction efficiency, greater damage risk, or greater wavefront distortion – bad !

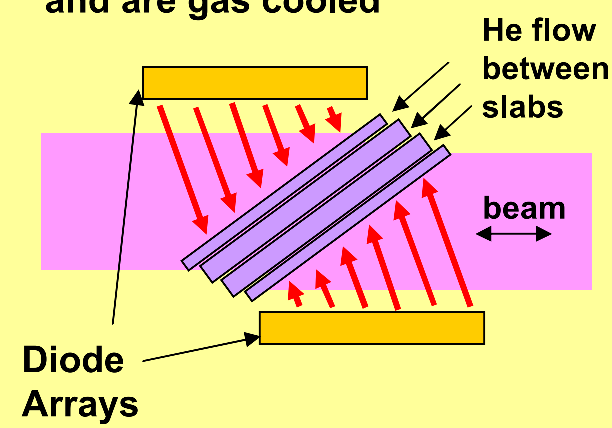
A Nd:glass laser with a NIF-like beamline design is a viable low-risk option – when diodes are cheap



- 20 kJ / beamline requires high-damage-threshold optics
- Overall wall-plug efficiency ~ 13%
- 100 beamlines are needed for a 2-MJ laser

	Diode costs	
Unit costs	@10¢ / W	@1¢ / W
20-kJ beamline	$26 M	$2.6 M
2-MJ system	$2600 M	$260 M

Brewster-angle slabs are stacked in groups of four and are gas cooled



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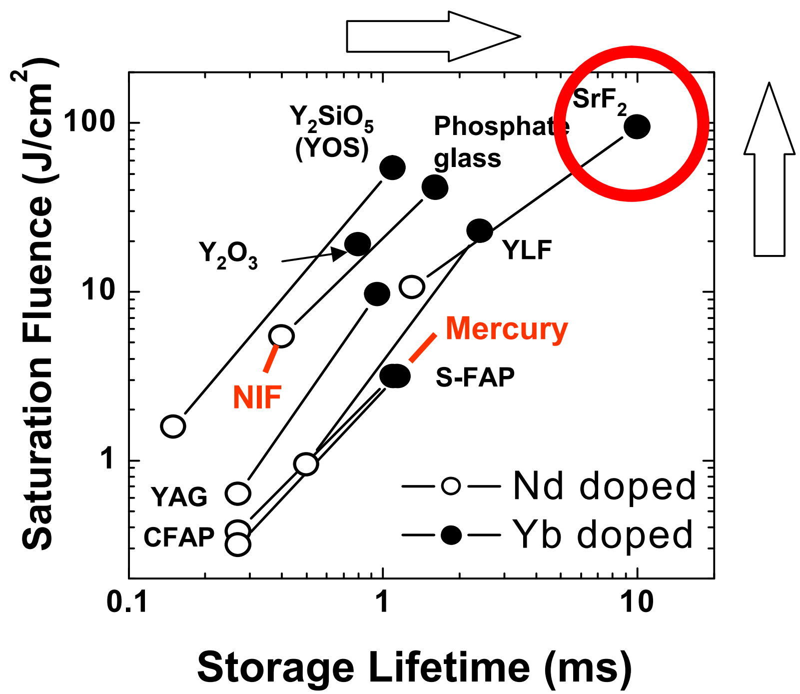


$$\phi_{sat} \propto \tau_{storage}$$

Higher stored energy density,
fewer laser slabs needed,
higher storage efficiency – good !

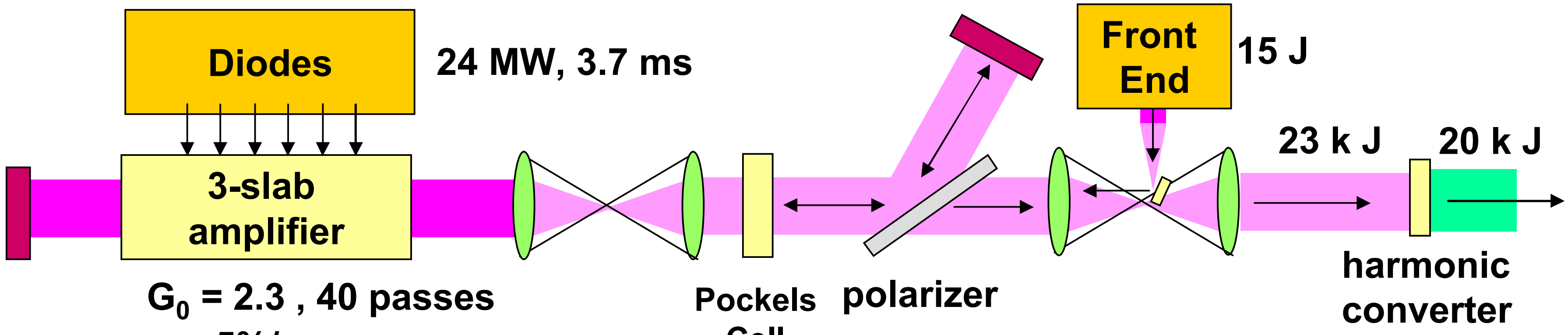
Lower extraction efficiency,
greater damage risk, or
greater wavefront distortion – bad !

Transparent ceramics are likely to revolutionize the manufacture of crystalline laser-gain media

- Strengths
  - Crystalline material but can be made in large sizes, like glass
  - Optical quality comparable to glass
  - Rapid development path due to many users

- Limitations
  - Currently require development in pulsed laser operation damage threshold
  - Today only applicable to cubic structures – YAG, Y_2O_3, SrF_2,

A Yb:SrF_2 multipass design would be attractive even when diodes are expensive



G_0 = 2.3 , 40 passes
α = 5%/cm
ρ = 5.75 J/cm^3

ϕ_{sat} = 115 J/cm^3
$\tau_{storage}$ = 9.2 ms

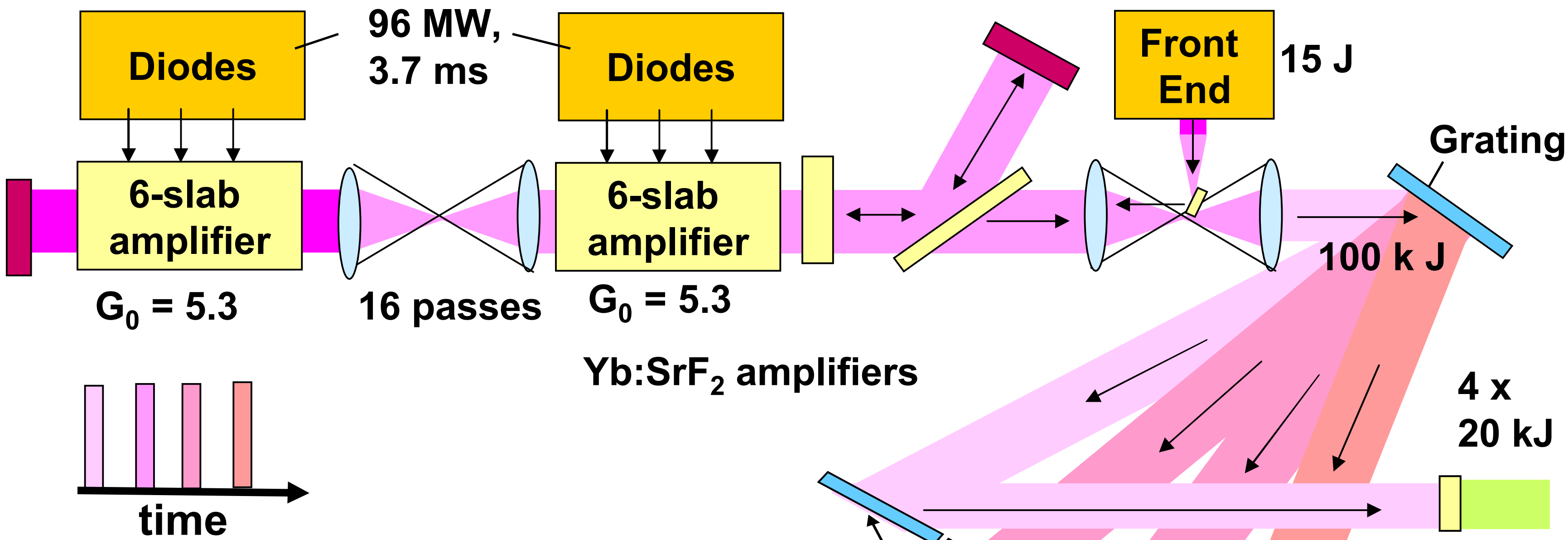
- 20 kJ / beamline
- Overall wall-plug efficiency ~ 13%
- 100 beamlines are needed for a 2-MJ laser

<u>Issues</u>

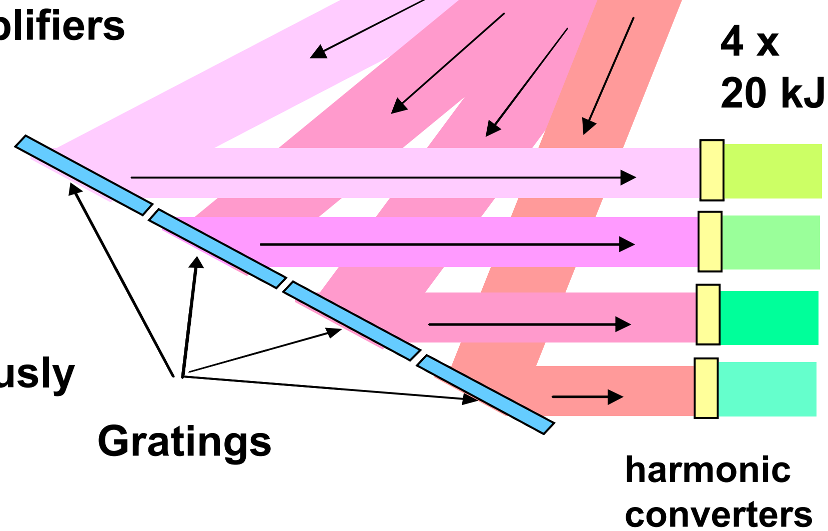
- Optical loss reduces extraction efficiency
- Optical damage risk
- Spatial-filter pinhole closure
- Heating of the Pockels Cell by absorbed light
- Wavefront distortion from many passes

	Diode costs	
Unit costs	@10¢ / W	@1¢ / W
20-kJ beamline	\$2.4 M	\$0.24 M
2-MJ system	\$240 M	\$24 M

Pulse-stacking methods can reduce beamline counts



- Four pulses of different wavelengths are separated by gratings
- Pulses arrive at target chamber simultaneously
- Wall-plug efficiency is ~14%



<u>Issues</u>

- Multipass issues from previous slide
- High-damage-threshold gratings
- Gain bandwidth, reduced gain in wings

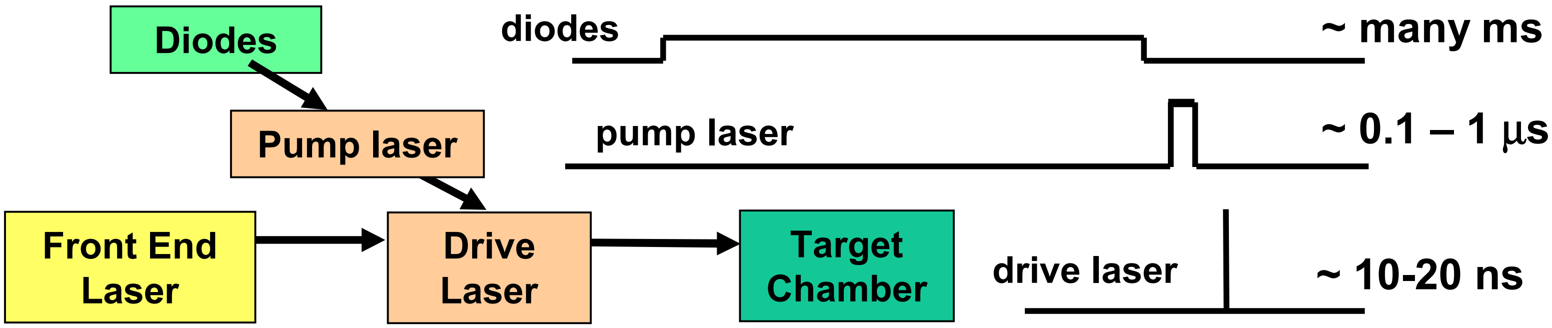
Only 25 beamlines are needed for a 2-MJ laser

But what if

- **diodes stay expensive**
- **damage thresholds stay low**
- **wavelength-division multiplexing doesn’t work out**

?

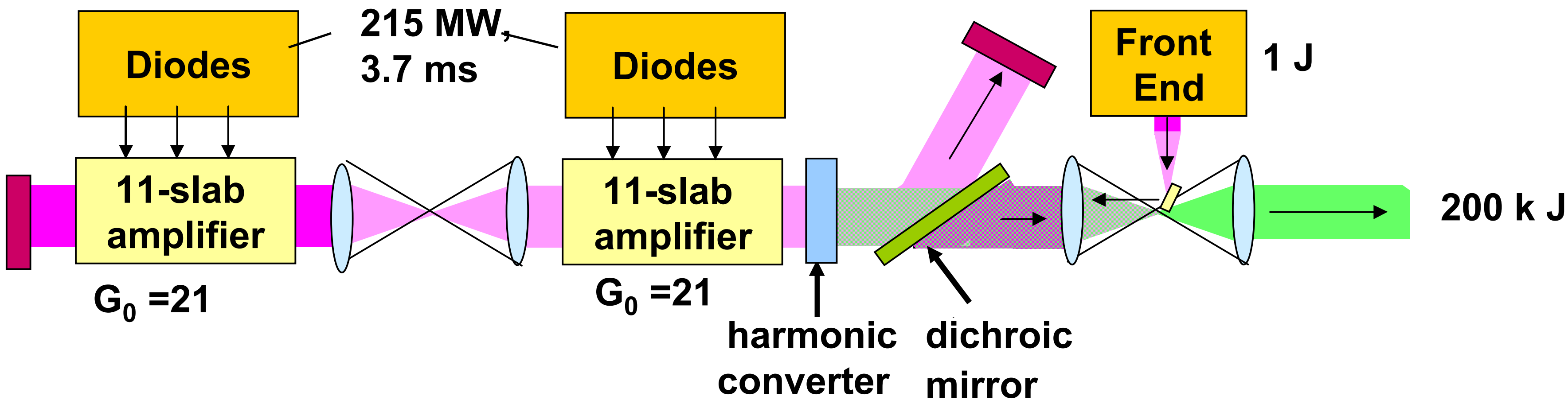
A possible solution is a laser-pumped laser



Idea:
Separate the two main amplifier functions so that each may be better optimized, separately
- a pump laser stores energy and pumps a drive laser
- the drive laser produces 10-20-ns compression pulses

- **Optimize pump laser for storage**
  - use gain medium with a long storage lifetime, high saturation fluence
  - extracting at high fluence is OK when pulselengths are 100s of ns long
- **Optimize the drive laser for producing 10-20 ns-long pulses**
  - use gain medium with low saturation fluence, short storage lifetime
  - short storage lifetime is OK since energy is extracted $< 1\mu s$ after pumping

A pump-laser design using Yb:SrF_2 produces 200 kJ per beamline at 0.5μm

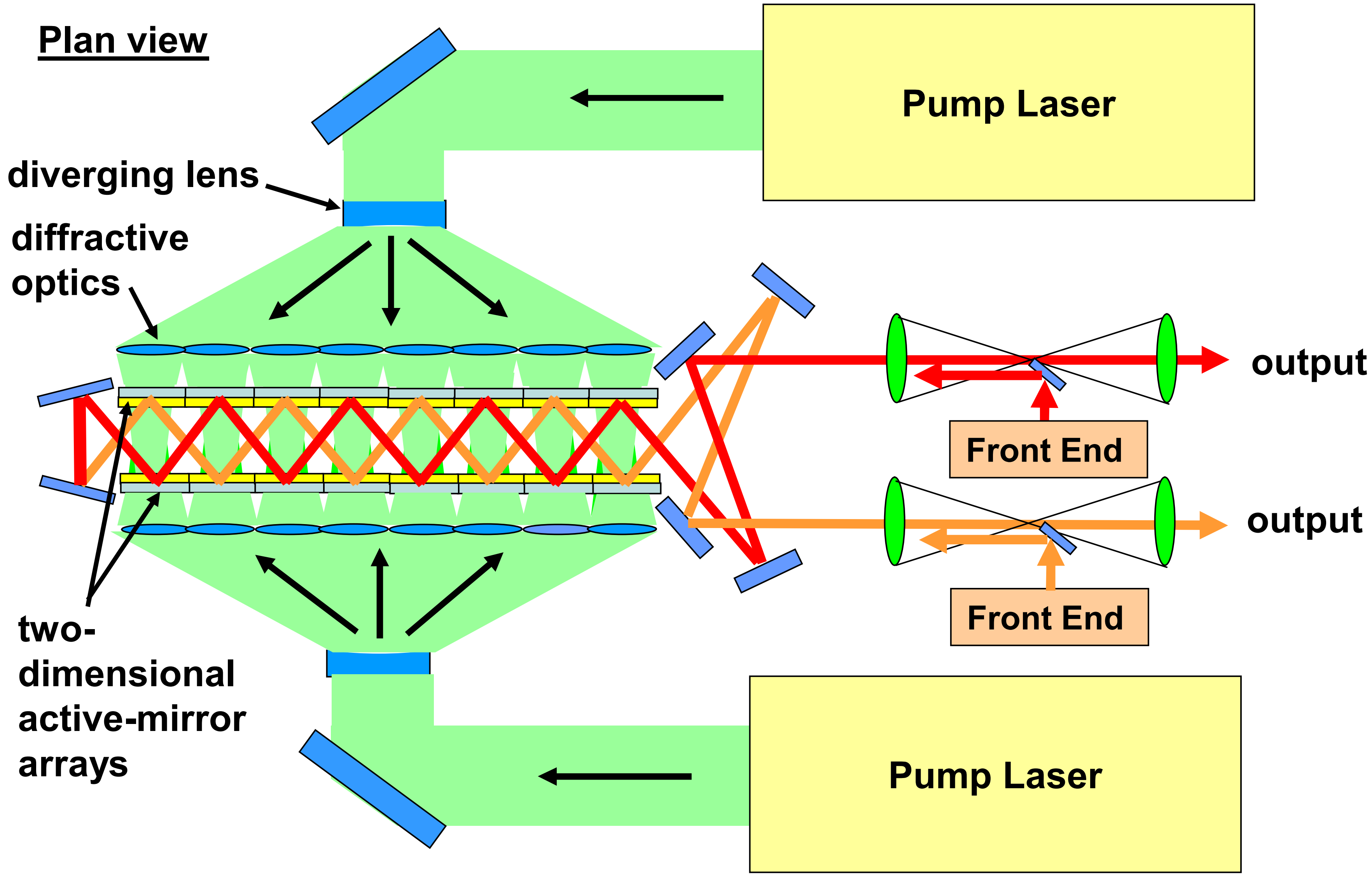


Damage fluences are 100s of J/cm^2 at pulselengths of 100s of ns

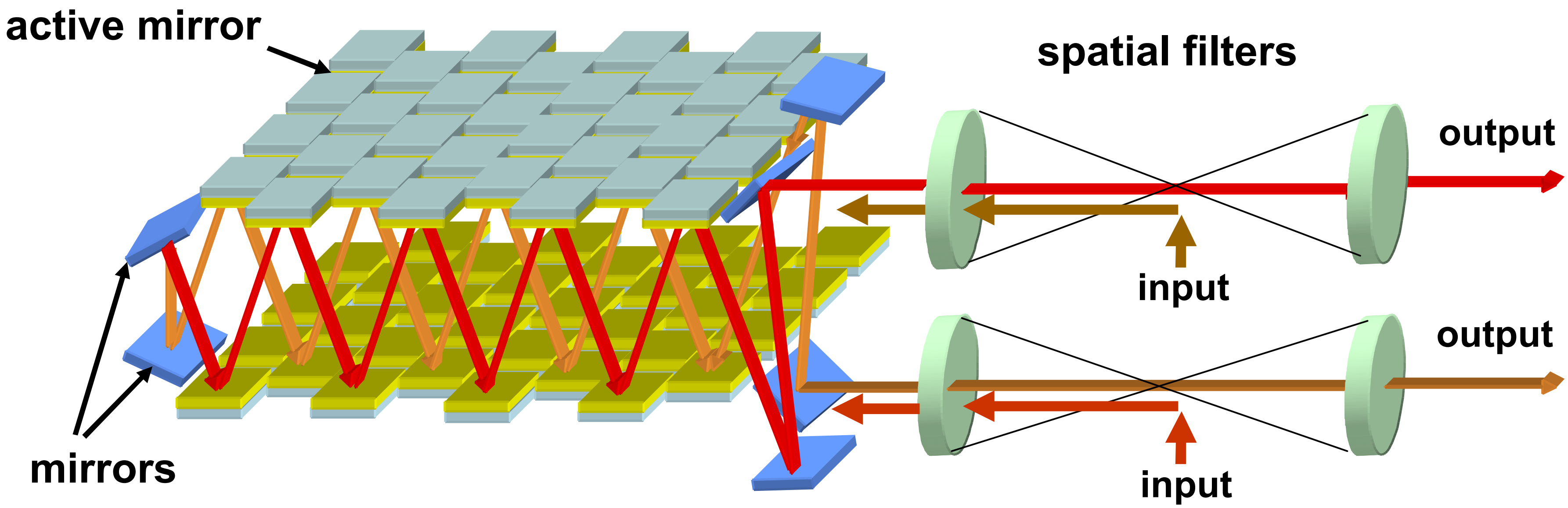
- damage fluences scale as ~ $\tau^{1/2}$

- With internal harmonic converter, ~70% of stored energy can be converted and output at ~0.5 μm over several 10s of passes
  - no Pockels Cell switch needed for switching, but gain must be held off during pumping, possibly with a saturable absorber
  - 0.5-μm light can pump titanium-doped sapphire lasers
  - converter requires development
- Poor beam quality is OK
- Only ~15-20 beamlines are needed to pump the driver beam lines of a 2-MJ compression laser

Pump light is delivered through the sides of the active-mirror arrays



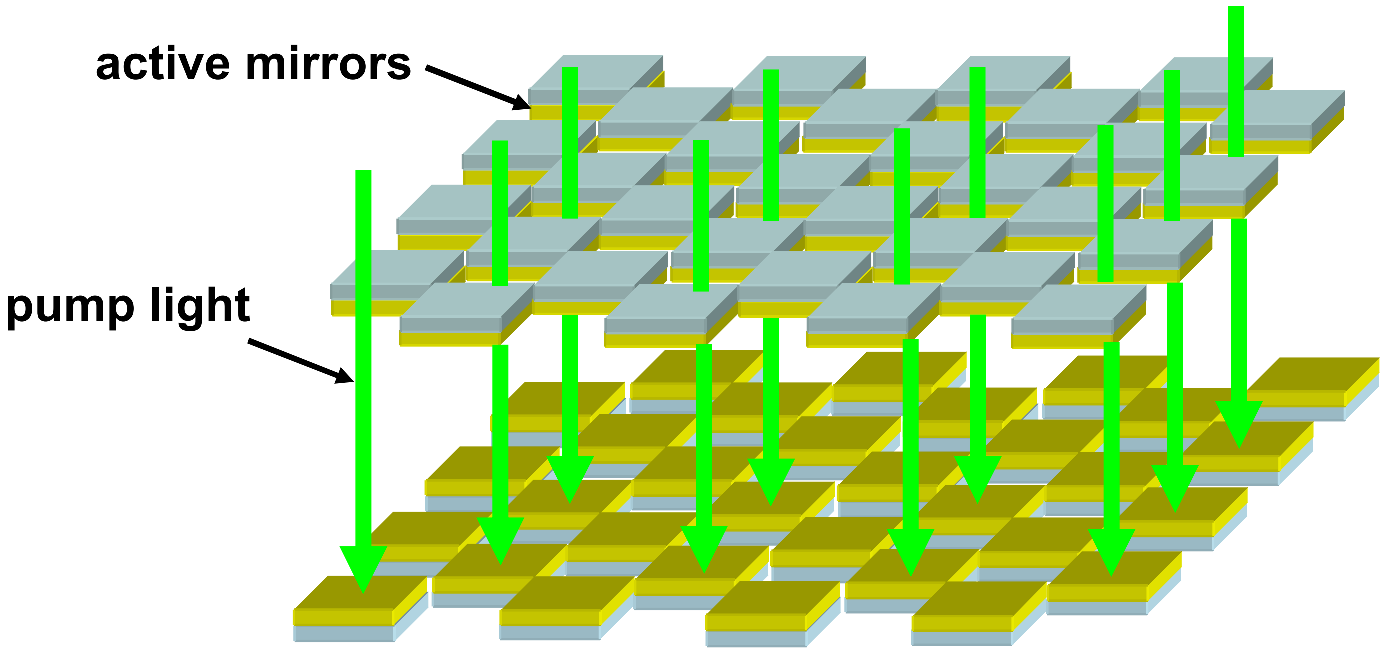
Amplifier cavities can be set up around the active-mirror arrays by using mirrors and spatial filters



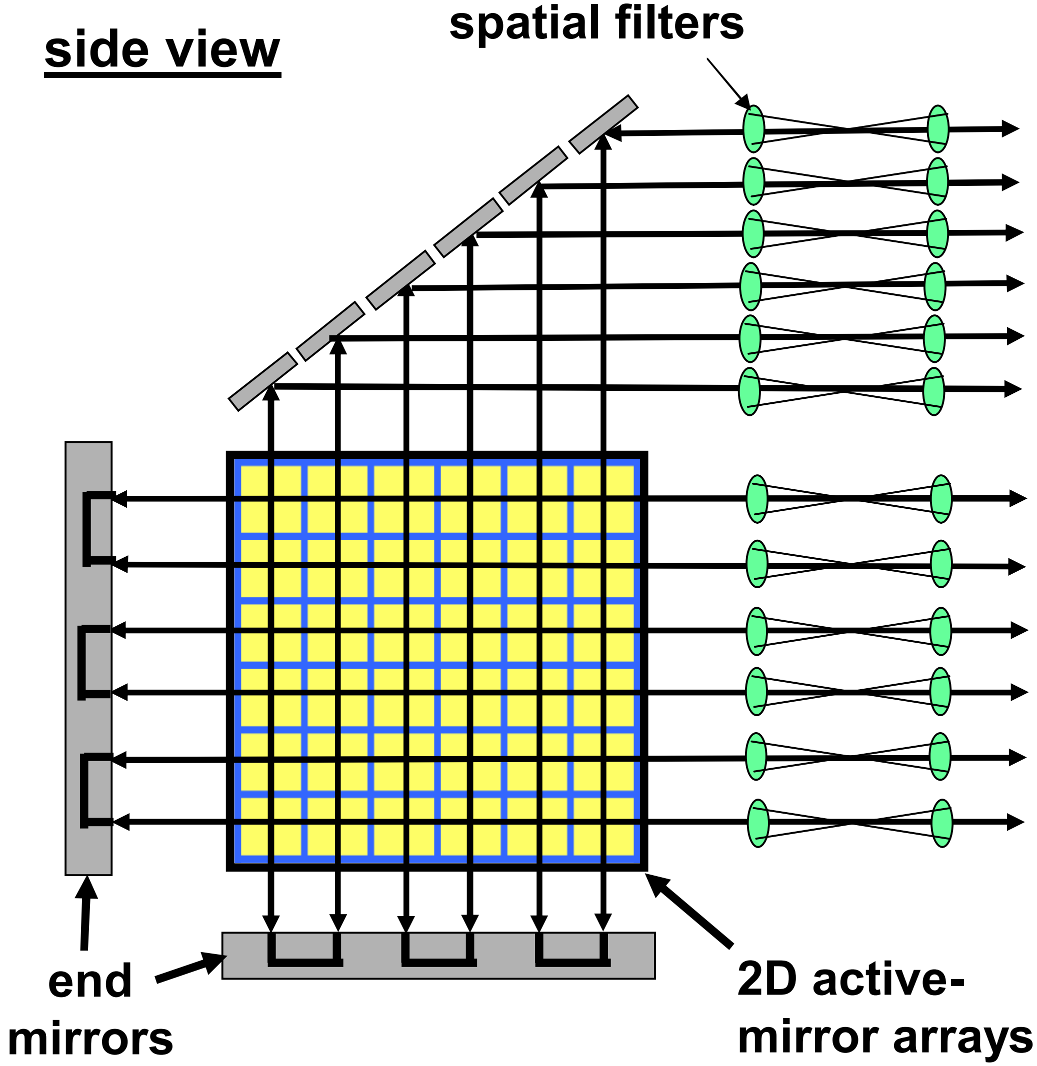
- Only one pair of beamlines are shown here, for clarity

- Not shown are:
  - beam lines that are parallel to the illustrated beamlines
  - beam lines that are orthogonal to the illustrated beamlines

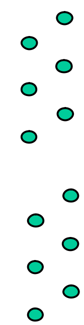
Pump light for each array is delivered through openings in the facing array



A side view shows how beamlines enter and exit the array



beam output, end view



- Amplifiers are compact

-Each laser slabs helps to amplifier 4 laser beams

- In this example, 36 active mirrors produce 12 laser beams

- Larger arrays with each beam encountering more slabs is probably desirable

Significant increases in laser efficiency appear to be possible

Eff. (%)	NIF	Future DPSSL
Power Conditioning	82	87 - 93
Diodes / Lamps	50	70 - 90
Pump transport	60	91 - 99
Absorption	40	91 - 99
Quant Defect	60	83 - 93
1 – Decay Fraction	45	58 - 82
Extraction & Fill	51	60 - 90
Beam transport	93	93 - 99
Freq Conv	60	85 - 95
Cooling	NA	83 - 93
Total (%)	0.75	15 - 30

- There are tradeoffs between capital costs and efficiency
- It is our job to study tradeoffs for practical systems

Laser "skunkworks" activities have been undertaken to develop low cost, high-efficiency laser drivers

Our work builds upon experience building large flashlamp-pumped laser systems and smaller diode-pumped systems

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